

Microquasars

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Abstract. I partially review our current knowledge on microquasars, making special emphasis on radio interferometric observations, and I comment on emerging trends in this field of astrophysics.

1. X-ray binaries, radio emission and microquasars

An X-ray binary is a binary system containing a compact object, either a neutron star or a stellar-mass black hole accreting matter from the companion star. The accreted matter carries angular momentum on its way to the compact object, around which, in most cases, forms an accretion disk responsible for the X-ray emission. The most recent catalogs contain a total of 280 X-ray binaries (Liu, van Paradijs, & van den Heuvel 2000; Liu, van Paradijs, & van den Heuvel 2001). In 131 of such systems the companion star has a spectral type O or B, and they are classified as High Mass X-ray Binaries (HMXBs), where mass transfer takes place via a decretion disk (in Be stars) or via a strong stellar wind or Roche-lobe overflow (in OB supergiants). In 149 X-ray binaries the optical companion has a spectral type later than B, and they are called Low Mass X-ray Binaries (LMXBs), where mass transfer occurs via Roche-lobe overflow.

Among them, this author has found 43 Radio Emitting X-ray Binaries (REXBs), of which 8 are HMXBs that usually show persistent radio emission and 35 are transient LMXBs. Since the detected radio emission (in nearly all cases) displays nonthermal spectra, shows some degree of polarization, and implies high brightness temperatures, it is interpreted as produced by the synchrotron radiation mechanism, which takes place when we have charged particles accelerated in the presence of magnetic fields.

A microquasar is simply a REXB displaying relativistic radio jets that can be imaged at a variety of angular scales using different interferometers. Due to the lack of space, I refer the reader to Mirabel & Rodríguez (1999) and to Fender (2004) for extended reviews on the topic (including discussion on emission mechanisms, relativistic effects, observed radio/X-ray correlations, energetics, jet formation, etc.). The name microquasar was given not only because of the observed morphological similarities between these sources and the distant quasars but also because of physical similarities, since when the compact object is a black hole, some parameters appear to scale with the mass of the central object. In this context, the temperatures of the inner parts of the accretion disks are of the order of $\sim 10^7$ K in the case of microquasars containing stellar-mass black holes and $\sim 10^5$ K in the case of quasars containing supermassive black

holes (10^6 – $10^9 M_\odot$). This explains why in microquasars the accretion luminosity is radiated in X-rays, while it is done in the optical/UV domain in the case of quasars, and why we had to wait until the era of high-energy astrophysics to discover these sources. On the other hand, the characteristic jet sizes seem to be proportional to the mass of the black hole, since radio jets in microquasars have typical sizes of the order of light years, while radio jets in quasars reach distances up to several million light years in giant radio galaxies. Last, but not least, the timescales are also directly scaled with the mass of the black hole following $\tau \simeq R_{\text{Sch}}/c = 2GM_X/c^3 \propto M$, being R_{Sch} the Schwarzschild radius. Therefore, phenomena that take place in timescales of years in quasars can be studied in minutes in microquasars. In this sense, one can say that microquasars mimic, on smaller scales, many of the phenomena seen in AGNs and quasars, but allow a better and faster progress to understand the accretion/ejection processes that take place near compact objects. However, it should be noted that the angular scales in units of R_{Sch} are much higher for nearby quasars than for microquasars, allowing a *closer* look to the jet formation region.

The number of currently known microquasars is around 16 (Ribó 2002), among the 43 catalogued REXBs. It is interesting to note that some authors (e.g., Fender 2004) have proposed that all REXBs are microquasars (i.e., radio emission is always in the form of relativistic jets), and would be detected as such provided that there is enough sensitivity and/or resolution in the radio observations (some of them conducted in the past). In fact, we have detected radio jets in all REXBs for which detailed observations have been possible, with the only exception of CI Cam. Moreover, it has been suggested that all X-ray binaries, except X-ray pulsars that disrupt the inner part of the accretion disk where the jets are supposed to be launched, have relativistic jets (Fender 2004). In this context, all of them should be considered microquasars. Although this is a reasonable hypothesis, only deep radio observations of the faint X-ray binary population will allow to confirm or reject it. The planned improvement of existing radio interferometers will definitely help to solve this important issue.

2. Types of jets

Radio jets have been imaged with different radio interferometers (including the VLA, VLBA, EVN, MERLIN, ATCA, SHEVE and LBA). Broadly speaking, we can find the following types of jets.

- **Compact jets.** These jets have been resolved mainly with the use of the VLBA. Two examples of AU-scale jets are shown in Fig. 1. In the case of GRS 1915+105 the compact jet appears in the so called ‘plateau’ state (see Dhawan, Mirabel, & Rodríguez 2000 and Fuchs et al. 2003). In Cygnus X-1 the compact jet is present during the canonical low/hard black hole state (Stirling et al. 2001). This type of jet displays a flat or inverted radio spectral index ($\alpha \geq 0$, where $S_\nu \propto \nu^{+\alpha}$), as one would expect from optically thick synchrotron emission in a continuous jet flow (see Fender 2001 and references therein). Therefore, its presence has been inferred in other black hole candidates where high resolution imaging is not possible due to their flux density and position in the sky, like in the case of GX 339–4. The flat spectrum has been shown to extend up to mm, IR and probably optical wavelengths, and even the X-ray emission

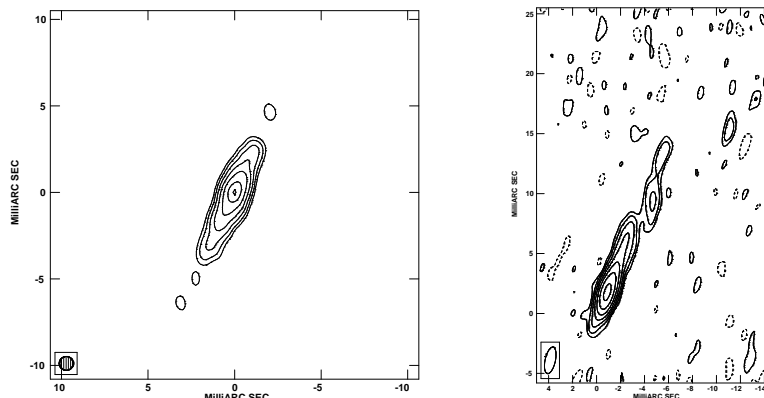


Figure 1. VLBA images of compact radio jets. Left: GRS 1915+105 (from Dhawan et al. 2000). Right: Cygnus X-1 (from Stirling et al. 2001).

could be interpreted as optically thin synchrotron emission produced at the base of the jet. This is suggested by the X-ray/radio correlation spanning more than three orders of magnitude in luminosity found in the low/hard state (see Gallo, Fender, & Pooley 2003 and references therein).

- **Discrete ejections.** These ejections take place during ‘state transitions’ in black hole candidates. The most representative examples are the superluminal ejections of GRS 1915+105 (Mirabel & Rodríguez 1994; Fender et al. 1999) and GRO J1655–40 (Hjellming & Rupen 1995; Tingay et al. 1995). In these cases the radio emission rapidly evolves to an optically thin spectrum (negative spectral index α), in agreement with adiabatic expansion of the relativistic electron clouds. Although the Lorentz factors are not well constrained due to uncertainties in the distance to the sources, it has been shown that they have $\Gamma \geq 2$. It should be noted that the neutron star Sco X-1 shows isolated ejections ‘moving’ at $\beta \simeq 0.45$ ($\Gamma \simeq 1.1$) that experience a rebrightening compatible with an underlying jet flow with $\beta \geq 0.95$ ($\Gamma \geq 3$) (Fomalont, Geldzahler, & Bradshaw 2001). The moving components are interpreted in this case as the result of jet-ISM interaction. On the other hand, Cygnus X-3 appears to display a one-sided relativistic jet at VLBI scales (Mioduszewski et al. 2001) that may slow down due to interaction with the ISM and end up as a discrete (isolated) two-sided mildly relativistic jet (Martí, Paredes, & Peracaula 2000; Martí, Paredes, & Peracaula 2001).

- **Large-scale jets.** Parsec-scale radio jets have been imaged in the two galactic center hard X-ray sources, namely 1E 1740.7–2942 and GRS 1758–258 (Mirabel et al. 1992; Martí et al. 2002). Since these sources have been found most of times in the low/hard state, the large-scale jets are thought to result from the long-term action of steady jets on the ISM. On the other hand, the radio nebula W50 around the well-known microquasar SS 433 is clearly distorted by the interaction of the jet with it, which produces as well extended X-ray jets that were detected with the ROSAT satellite. However, one of the most impressive detections of the jet-ISM interaction are the simultaneous X-ray (Chandra) and

radio (ATCA) observations of decelerating relativistic jets in the microquasar XTE J1550–564 (Corbel et al. 2002). The detected X-ray and radio emissions, imaged a few years after a major ejection and located at around 0.6–0.7 pc from the binary system, are probably produced by synchrotron radiation mechanism, which takes place when particles are accelerated in an external shock wave originated when the jet material interacts with the ISM. It should be noted that a similar event could have been observed, but only at radio wavelengths, in the source XTE J1748–248 (Hjellming, unpublished). Finally, one of the latest results on jet-ISM interaction has been the detection with XMM of extended X-ray jets spanning ~ 3.5 arcminutes in the X-ray binary 4U 1755–338 (Angelini & White 2003). Assuming a distance to the source of 4 kpc these X-ray jets extend up to 4 pc, as do the radio jets of the galactic center source GRS 1758–258.

An interesting case that does not fit in the ones explained above is that of LS 5039, where a compact radio jet, but showing discrete components, has been detected at AU-scales (Paredes et al. 2000). Moreover, the radio spectral index is $\alpha \simeq -0.5$, indicative of optically thin emission, in contrast with the flat spectral index detected in the low/hard state of black hole candidates (the nature of the compact object in this source is not yet known, although the radial velocity curve supports a neutron star). This suggests that the compact jet is build up in the superposition of subsequent discrete ejections, although this is an idea that has still to be checked.

It should also be noted that simultaneous X-ray, IR and radio observations of GRS 1915+105 reveal that during episodes of rapid disappearance and follow up replenishment of the inner accretion disk ejection of relativistic plasma clouds are produced. These ejections can be understood as small-scale analogs of the more massive discrete superluminal ejecta of the source (Mirabel et al. 1998). It is interesting to note that similar phenomena have been recently observed in the quasar 3C 120, but in timescales of years (Marscher et al. 2002).

Apart from the jet features discussed above, extended equatorial radio emission has been detected with the VLBA and MERLIN in the microquasar SS 433 (Paragi et al. 1999; Blundell et al. 2001). Although the observed flat spectral index suggests thermal emission or self-absorbed synchrotron emission, its nature is not yet well understood.

3. Astrometry and stellar evolution

An emerging trend in microquasars is the study of the space velocity of the systems, that can be related to the SN explosion of the compact object progenitor. The basic idea is to combine the radial velocity of the system with accurate proper motions and the distance to the source to obtain the total space velocity of the system. Once this is known, we can assume a mass model for the Galaxy, compute the galactocentric orbit of the system and look for the parent association of the binary system or the related SN remnant. In both cases this allows to constrain the age of the binary system after the SN explosion. The observed velocity (relative to the association or remnant if available) can be compared with the expected one after assuming different mass-losses in the SN explosion through basic formulae (in the case of symmetric SN explosions) or through Monte-Carlo simulations (in the case of asymmetric SN explosions with kicks).

All this information, specially the mass-loss during the SN explosion, can shed light on the final stages of stellar evolution.

It is clear that the compact jets in microquasars, imaged with VLBI techniques, allow a better measurement of the positions (and proper motions) of the binary systems than do the optical/IR telescopes (at least nowadays). Therefore, although this approach was used in the past basically with radial velocity measurements and upper limits to the proper motions, microquasars allow a much better and faster study. To this author, the most interesting results obtained up to now are: an age of ~ 7 Gyr for the system XTE J1118+480, that was probably formed in the galactic halo (Mirabel et al. 2001); a runaway velocity of 150 km s^{-1} in the case of LS 5039 (Ribó et al. 2002a), implying an amazingly huge linear momentum of $\sim 6000 M_{\odot} \text{ km s}^{-1}$ and a huge mass-loss of at least $6 M_{\odot}$ during the SN explosion; a delayed black hole formation in the case of GRO J1655–40 (Mirabel et al. 2002) and a prompt black hole formed in the case of Cygnus X-1 (Mirabel & Rodrigues 2003). Similar studies are in progress for the microquasars LS I +61 303 and GRS 1915+105.

4. Gamma-rays, matter content, neutrinos and ULXs

Paredes et al. (2000) have suggested that the microquasar LS 5039 could be related to the high-energy γ -ray source 3EG J1824–1514. The proposed physical interpretation of this emission is that UV photons from the luminous optical companion experience inverse Compton scattering by the same relativistic electrons that later, after having lost part of their original energy due to IC losses, will account for the radio emission in the jets (Paredes et al. 2002). A similar scenario could be at work in LS I +61 303 (Massi et al. 2001, 2004). These findings open up the possibility that other unidentified EGRET sources could be microquasars. Using these ideas as the starting point, Kaufman Bernado, Romero, & Mirabel (2002) have studied the general problem of γ -ray emission arising by inverse Compton scattering of external photon fields by the electrons of the jets in microquasars. In this context, they have suggested that some of the unidentified variable EGRET sources could be precessing microblazars.

The matter content of the jets is only known in the microquasar SS 433, where iron lines from the jet have been spatially resolved with Chandra (see Migliari, Fender, & Méndez 2002 and references therein). Moreover, if the jets are hadronic we would expect the formation of TeV neutrinos, that could be detected in the future with detectors of km^2 -scale effective area (Distefano et al. 2002). However, some models to explain jet formation only work for e^-e^+ plasma. Therefore, the observational study of jets to unveil their matter content is of prime importance to better understand the jet formation mechanism.

UltraLuminous X-ray sources (ULXs) are off-nuclear X-ray sources in external galaxies, with computed isotropic X-ray luminosities above the Eddington luminosity for stellar-mass black holes (see e.g. Makishima et al. 2000 and references therein). ULXs have been interpreted as evidence for intermediate-mass black holes. However, Kaaret et al. (2003) have recently shown that the multi-wavelength behavior of the ULX 2E 1400.2–4108 in NGC 5408 is consistent with beamed emission of a relativistic jet from a stellar-mass black hole, supporting the idea that microquasars in external galaxies could produce ULXs.

5. A search for new *persistent* microquasars

As discussed above, microquasars offer a unique opportunity to study accretion/ejection and related phenomena in human timescales. However, the current number of this kind of sources is not very high, and it would be desirable to enlarge the sample. Since the approach to discover new persistent microquasars was successful in the case of the HMXB LS 5039 (Paredes et al. 2000; Paredes et al. 2002), these authors started a long-term project to discover new similar sources based on a cross-identification between the ROSAT All Sky Survey Bright Source Catalogue and the NRAO VLA Sky Survey. Although the first results were promising (Paredes, Ribó, & Martí 2002; Ribó et al. 2002b), recent optical spectroscopic observations (Martí et al. 2004) reveal that most of the six studied sources, if not all, are extragalactic quasars.

Therefore, persistent (probably HMXB) microquasars do not appear to be common objects in the Galaxy. Nevertheless, it should be pointed out that deeper and harder X-ray surveys and/or deeper radio surveys, to be conducted in the future, could change the current situation.

Anyhow, these results stress the importance of studying the already known REXBs, where radio jets have not been yet clearly resolved but are thought to exist (Fender 2004), to better understand the involved physics. As an example, I point out that well-known REXBs like Cygnus X-1 and LS I +61 303 were only found to display jets after several years of detailed observations (Stirling et al. 2001; Massi et al. 2001; Massi et al. 2004).

6. Conclusions

Microquasars allow to gain insight into jet physics (including formation, matter content, propagation and interaction with the ISM), and on the origin and evolution of black holes. They could also be sources of high-energy γ -rays and TeV neutrinos, and eventually be ULXs. There are still lots of open questions that hopefully we will be able to answer with the advent of new instrumentation.

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References

- Angelini, L., & White, N. E. 2003, ApJ, 586, L71
- Blundell, K. M., Mioduszewski, A. J., Muxlow, T. W. B., Podsiadlowski, P., & Rupen, M. P. 2001, ApJ, 562, L79
- Corbel, S., Fender, R. P., Tzioumis, A. K., et al. 2002, Science, 298, 196
- Distefano, C., Guetta, D., Waxman, E., & Levinson, A. 2002, ApJ, 575, 378
- Dhawan, V., Mirabel, I. F., & Rodríguez, L. F. 2000, ApJ, 543, 373
- Fender, R. P., Garrington, S. T., McKay, D. J., et al. 1999, MNRAS, 304, 865
- Fender, R. P. 2001, MNRAS, 322, 31

- Fender, R. P. 2004, in 'Compact Stellar X-Ray Sources', eds. W. H. G. Lewin and M. van der Klis, Cambridge University Press, in press [astro-ph/0303339]
- Fomalont, E. B., Geldzahler, B. J., & Bradshaw, C. F. 2001, *ApJ*, 558, 283
- Fuchs, Y., Rodriguez, J., Mirabel, I. F., et al. 2003, *A&A*, 409, L35
- Gallo, E., Fender, R. P., & Pooley, G. G. 2003, *MNRAS*, 344, 60
- Hjellming, R. M., & Rupen, M. P. 1995, *Nature*, 375, 464
- Kaaret, P., Corbel, S., Prestwich, A. H., & Zezas, A. 2003, *Science*, 299, 365
- Kaufman Bernadó, M. M., Romero, G. E., & Mirabel, I. F. 2002, *A&A*, 385, L10
- Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2000, *A&AS*, 147, 25
- Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2001, *A&A*, 368, 1021
- Makishima, K., Kubota, A., Mizuno, T., et al. 2000, *ApJ*, 535, 632
- Marscher, A. P., Jorstad, S. G., Gómez, J. L., et al. 2002, *Nature*, 417, 625
- Martí, J., Paredes, J. M., & Peracaula, M. 2000, *ApJ*, 545, 939
- Martí, J., Paredes, J. M., & Peracaula, M. 2001, *A&A*, 375, 476
- Martí, J., Mirabel, I. F., Rodríguez, L. F., & Smith, I. A. 2002, *A&A*, 386, 571
- Martí, J., Paredes, J. M., Bloom, J. S., et al. 2004, *A&A*, 413, 309
- Massi, M., Ribó, M., Paredes, J. M., Peracaula, M., & Estalella, R. 2001, *A&A*, 376, 217
- Massi, M., Ribó, M., Paredes, J. M., et al. 2004, *A&A*, 414, L1
- Migliari, S., Fender, R., & Méndez, M. 2002, *Science*, 297, 1673
- Mioduszewski, A. J., Rupen, M. P., Hjellming, R. M., Pooley, G. G., & Waltman, E. B. 2001, *ApJ*, 553, 766
- Mirabel, I. F., Rodríguez, L. F., Cordier, B., Paul, J., & Lebrun, F. 1992, *Nature*, 358, 215
- Mirabel, I. F., & Rodríguez, L. F. 1994, *Nature*, 371, 46
- Mirabel, I. F., Dhawan, V., Chaty, S., et al. 1998, *A&A*, 330, L9
- Mirabel, I. F., & Rodríguez, L. F. 1999, *ARA&A*, 37, 409
- Mirabel, I. F., Dhawan, V., Mignani, R. P., Rodrigues, I., & Guglielmetti, F. 2001, *Nature*, 413, 139
- Mirabel, I. F., Mignani, R., Rodrigues, I., et al. 2002, *A&A*, 395, 595
- Mirabel, I. F., & Rodrigues, I. 2003, *Science*, 300, 1119
- Paragi, Z., Vermeulen, R. C., Fejes, I., et al. 1999, *A&A*, 348, 910
- Paredes, J. M., Martí, J., Ribó, M., & Massi, M. 2000, *Science*, 288, 2340
- Paredes, J. M., Ribó, M., Ros, E., Martí, J., & Massi, M. 2002, *A&A*, 393, L99
- Paredes, J. M., Ribó, M., & Martí, J. 2002, *A&A*, 394, 193
- Ribó, M. 2002, PhD Thesis, Universitat de Barcelona
- Ribó, M., Paredes, J. M., Romero, G. E., et al. 2002a, *A&A*, 384, 954
- Ribó, M., Ros, E., Paredes, J. M., Massi, M., & Martí, J. 2002b, *A&A*, 394, 983
- Stirling, A. M., Spencer, R. E., de la Force, C. J., et al. 2001, *MNRAS*, 327, 1273
- Tingay, S. J., Jauncey, D. L., Preston, R. A., et al. 1995, *Nature*, 374, 141